Towards probabilistic entanglement of distant atoms

Marc Almendros, Albrecht Haase, Markus Hennrich, Felix Rohde, Carsten Schuck, and Jürgen Eschner
ICFO - Institut de Ciències Fotòniques
Parc Mediterrani de la Tecnologia, 08860 - Castelldefels (Barcelona), Spain
http:// www.icfo.es

Institut de Ciències Fotòniques

Abstract

Non-local entanglement is considered a key resource in future quantum information processing. One of its applications is the implementation of quantum communication schemes over long distances [1]. Such non-local entanglement has been realized e.g. between two photons [2] and between an atom and a photon [3].

The proximate step towards distributed quantum information processing is the generation of entanglement of distant massive particles like single atoms, as e.g. proposed by Cabrillo et al. [4]. This scheme relies on the projective measurement of photons scattered from two distant atoms after excitation by a common laser pulse.

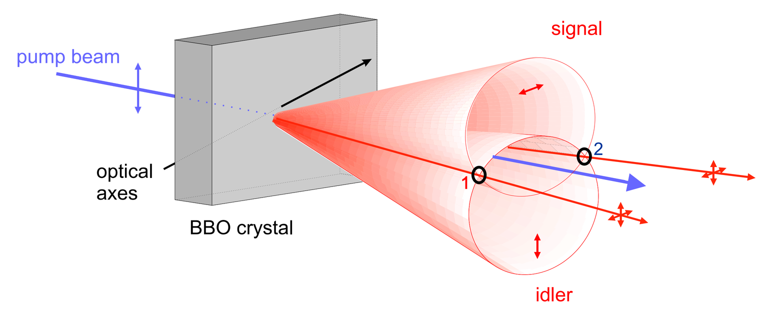
Here we describe our plans for an experimental realization of this scheme.

[1] H.-J. Briegel et al., Phys. Rev. Lett. **81**, 5932 (1998).
[2] P. G. Kwiat et al., Phys. Rev. Lett. **75**, 4337 (1995).
[3] B. B. Blinov et al., Nature 428, 153 (2004).
[4] C. Cabrillo et al., Phys. Rev. A **59**, 1025 (1999).

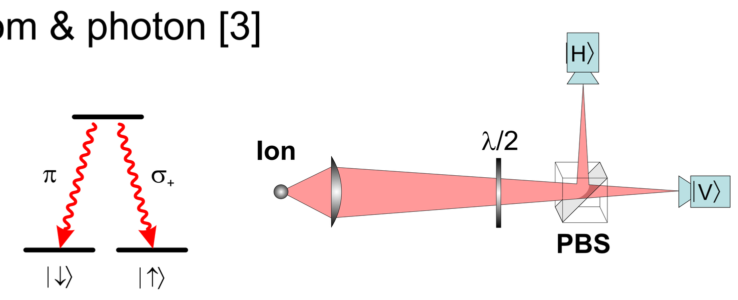
Previous experiments

Entanglement between two particles

- Photon pairs [2]



- Atom & photon [3]

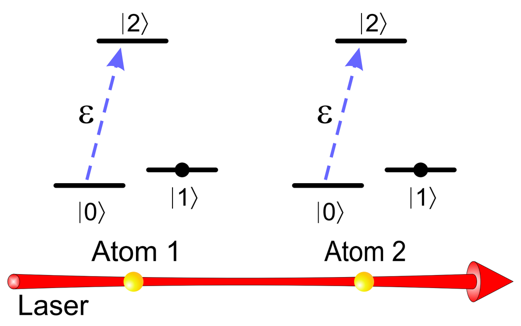


- Next step: entanglement of distant atoms
  - by long-range interaction?
  - by projective measurement [4]

Probabilistic entanglement

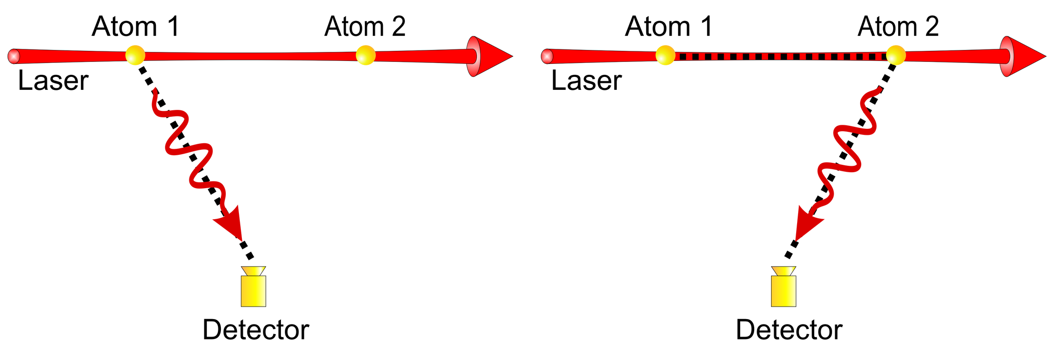
- **Initial state** $|\Psi_i\rangle = |0\rangle_1|0\rangle_2$
- **Weak excitation**

$$|\Psi'\rangle = |0\rangle_1|0\rangle_2 + \varepsilon\,(|2\rangle_1|0\rangle_2 + |0\rangle_1|2\rangle_2) + \varepsilon^2\,|2\rangle_1|2\rangle_2$$



- **Projective measurement: detect a scattered photon!**
- **Photon path indistinguishable**

photon scattered by atom 1 *or* by atom 2



→ Final entangled state: $|\Psi_f\rangle = |1\rangle_1|0\rangle_2 + e^{i\Phi}\,|0\rangle_1|1\rangle_2$
with relative phase Φ defined by path difference

- **Conditions**

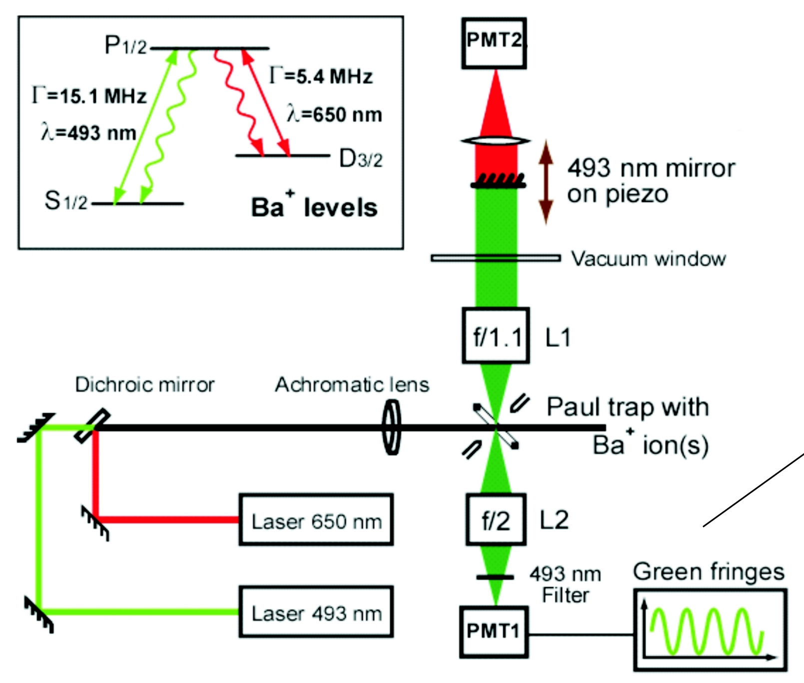
☑ not 2 scattered photons → weak excitation

☑ stable path difference → interferometric setup

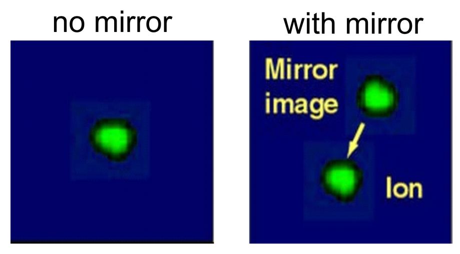
☑ no which-way information = no photon recoil → Lamb-Dicke regime

State-of-the-art

The Barium experiment in Innsbruck,
see e.g. J. Eschner, et al., Nature 413, 495 (2001)

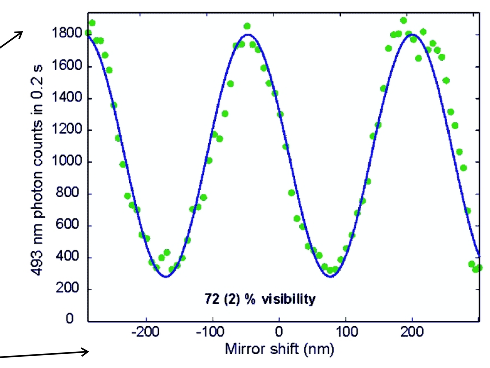


View through L2



- overlap ion's fluorescence with its mirror image

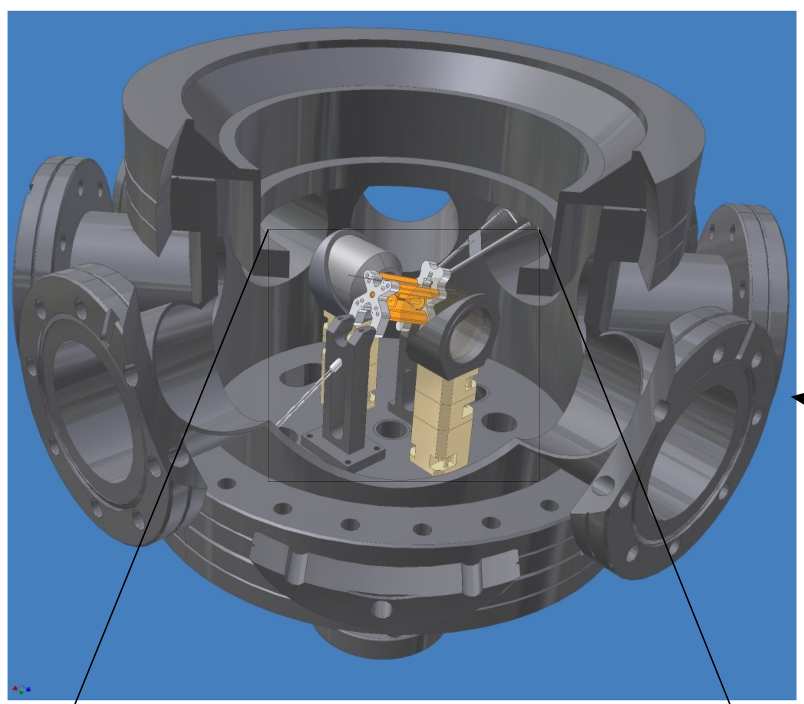
Interference signal



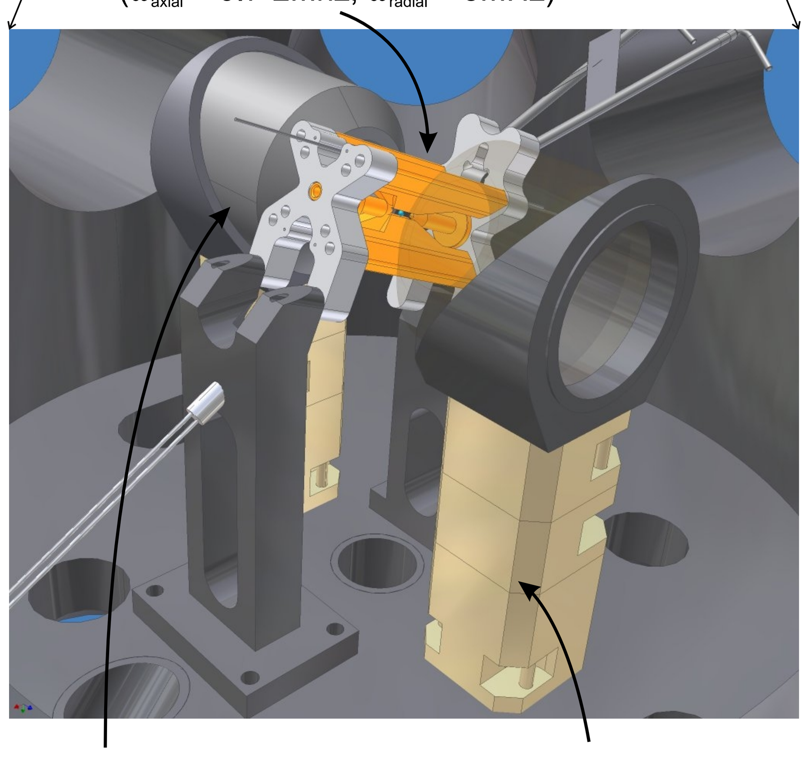
→ interference of spontaneous emission via a distance of 50cm
→ same technical requirements as for probabilistic entanglement

Intended setup

The vacuum chambers



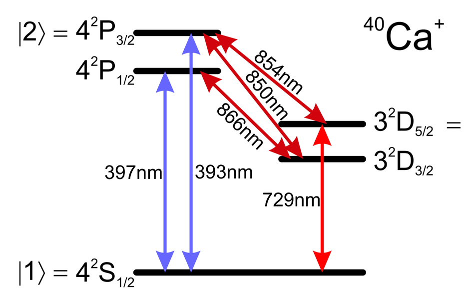
RF-trap
($\omega_{axial} \approx$ 0.7-2Mhz, $\omega_{radial} \approx$ 5MHz)



high-NA lenses

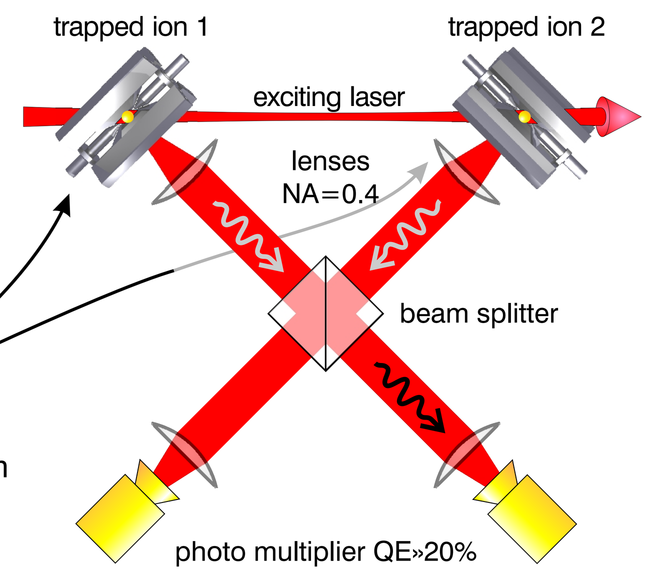
vacuum translation stages by attocube systems AG http://www.attocube.com

The ions



two such ion traps in two separate vacuum chambers at distance of ≅ 1 meter

Overview



Expected repetition rate

- Detection probability: $P_{det} = \eta_D \cdot \Omega \cdot 2\sin^2(\vartheta_{las})\cos^2(\vartheta_{las}) \cdot d \cdot l$

  - Detector quantum efficiency $\eta_D \sim 0.2$
  - Solid angle of collected fluorescence $\Omega \sim 0.04$
  - One and only one ion excited $2\sin^2(\vartheta_{las})\cos^2(\vartheta_{las}) = 0.18$
  - Pulse area of excitation pulse ϑ_{las}
  - Decay probability $|2\rangle \rightarrow |0\rangle$ $d \sim 0.92$
  - Losses induced by optical elements $l \sim 0.9$

  → $P_{det} \cong 0.001$

- Timing Sequence:
  - Doppler cooling ~3 ms
  - Manipulation and excitation ~32 μs
  - State detection ~6 ms

  ~10ms

  → Repetition rate ≅ 1000Hz

→ 1 entangled pair per 1 s

- Possible improvement:
  State detection conditional on photon detection

Conclusion

- Production of entangled states by projective measurement will be possible.
- Requires the combination of several most advanced ion trap technologies.
- Production of entangled states without Coulomb repulsion between ions or coupling of atoms to (cavity) field modes.

Outlook

- Small quantum networks: nodes (storage and local manipulation of qubits, Atoms) connected by quantum channels (communication by sending qubits, Photons).
- Distributed quantum computing and multiparty quantum communication based on probabilistic entanglement of distant atoms.
- Scalable quantum information processing with remotely located trapped ion qubits.